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Kaewunruen, Sakdirat; Mirza, Olivia

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Hybrid Discrete Element - Finite Element Simulation for Railway Bridge-Track Interaction

S Kaewunruen[1,2] and O Mirza[3]

[1]Department of Civil Engineering, The University of Birmingham, U.K
[2]Birmingham Centre for Railway Research and Education, The University of Birmingham, U.K
[3]Scool of Computing, Engineering and Mathematics, Western Sydney University, Australia

E-mail: s.kaewunruen@bham.ac.uk

Abstract. At the transition zone or sometimes called 'bridge end' or 'bridge approach', the stiffness difference between plain track and track over bridge often causes aggravated impact loading due to uneven train movement onto the area. The differential track settlement over the transition has been a classical problem in railway networks, especially for the aging rail infrastructures around the world. This problem is also additionally worsened by the fact that the construction practice over the area is difficult, resulting in a poor compaction of formation and subgrade. This paper presents an advanced hybrid simulation using coupled discrete elements and finite elements to investigate dynamic interaction at the transition zone. The goal is to evaluate the dynamic stresses and to better understand the impact dynamics redistribution at the bridge end. An existing bridge 'Salt Pan Creek Railway Bridge', located between Revesby and Kingsgrove, has been chosen for detailed investigation. The Salt Pan Bridge currently demonstrates crushing of the ballast causing significant deformation and damage. Thus, it's imperative to assess the behaviours of the ballast under dynamic loads. This can be achieved by modelling the nonlinear interactions between the steel rail and sleeper, and sleeper to ballast. The continuum solid elements of track components have been modelled using finite element approach, while the granular media (i.e. ballast) have been simulated by discrete element method. The hybrid DE/FE model demonstrates that ballast experiences significant stresses at the contacts between the sleeper and concrete section. These overburden stress exists in the regions below the outer rails, identify fouling and permanent deformation of the ballast.

1. Introduction

Railway bridges are generally constructed from various materials such as timber, steel and concrete. Each structural component has alternate functions and specific design features to suit their individual purpose for the track superstructure [1]. The constant action of the sleeper being put under train dynamic loads has a detrimental effect on the ballast bed below, which increases the rate of ballast degradation and breakage of ballast rocks as stated in Jing et al. [2]. The main ballast sleeper interaction occurs where the pressure is distributed from the sleeper as the dynamic loads of the train pass, to the ballast bed below where it is responsible for both horizontal and perpendicular support. Vertical support is important as it provides a good elastic bed for support and supports the rails evenly. Horizontal support is also vital as it stops the buckling of rails and resisting the lateral movement of the train. The dynamic interactions of the ballast bed have focused around three main areas of ballast contact forces, sleeper settlement and ballast breakage as seen in Figure 1.

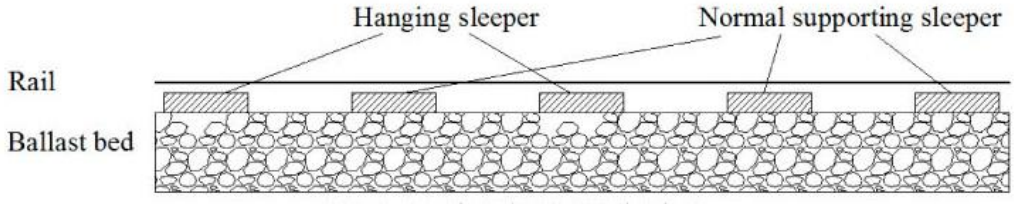


Figure 1. Section of railway structure, variation of normal and hanging sleepers [2].

Ballast structure is responsible for the distribution and absorbing of dynamic impact loads from trains moving above. The frequent passing of trains generates plastic distortion within the ballast particles and the accumulation of these over time will cause deformation amongst the ballast as well as uneven settlement and reduced stiffness. Due to these phenomena, Aikawa [3] states that therefore frequent and periodic maintenance of ballast structure must occur, thus causing the need to further investigate and research the effects and interactions of sleepers and ballast. Due to modern innovations and increased axle loadings placed on trains, new maintenance methods must be sought after to ensure that servicing and repair occurs within a reasonable amount of time. As a high-speed train passes over a ballasted track, it transfers low frequency vibrations due to the dynamic axle loads. However, Aikawa [3] states that these particles will also be susceptible to high frequency vibrations due to the sudden impact loading placed by the rolling wheel contact force. The ballast particle sharp corners mean that forces are concentrated through a point leading to fouling of the ballast and particle breakage which are the main causes of ballast degradation.

The results of the sleeper deformation and load distribution suggest that the bottom of the sleeper is evenly under force. The natural bounce mode, which is the upward and downward movement of the sleeper, occurs at 45 Hz with the first bending moment occurring at 180 Hz with both ends of the sleeper vibrating strongly as stated by Aikawa [3]. The second bending vibration moment occurs at 400 Hz with the third bending moment occurring at 860 Hz. Acceleration responses of the sleeper and ballast were measured at 10 centimetres below the underside of the sleeper, with results showing a wide range of frequencies placed on the ballast and sleeper structures. The wide range is the result of both low frequency dynamic trainloads and high frequency impact loads placed on the structure from the rolling wheel loads causing a sharp peak in the results. Aikawa [3] stated that the displacement occurs whilst frequencies are low, once frequency is greater than 100 Hz the displacement is very small around 10^{-7} m of settlement occurring. The frequency of the third bending moment (800 Hz) provides a extremely small ballast amplitude of 10^{-9} m. These results concluded that high frequency impact loads, over 100 Hz decreased in terms of the load transfer substantially. Moreover, lower frequency impact loads on the rigid and stiff ballast layer, caused resistance problems for the ballast structure especially at 10 Hz or less [4-6]. Aikawa [3] stated that this is mainly due to the fact that ballast's main function of support and resistance occurs in proportion to the mass that is placed on it.

2. Railway Bridge Case

Salt Pan Creek Railway Bridge is located on the East Hills line, south of the M5 Motorway in Sydney, New South Wales (NSW) Australia. Salt Pan Creek is the first bridge in Australia to be incrementally launched, which was mainly due to the environmental sensitivity of the local ecosystem in the region. The new bridge is vital to the linking of the east and west regions separated by the bridge. The bridge contains a quadrupled track as part of the NSW government's railway clearways program, which had the main focus of increasing the flow capacity of the railway system between the Kingsgrove and Revesby stations. The bridge contains six spans with span one and six being of 18m long whilst the 4 middle spans having a length of 32m. All four piers, containing two columns each, are constructed of 50MPa concrete, piled into the rock bed underneath the Salt Pan Creek River. The superstructure is composed of composite concrete-steel sections, which are created through a single pour process. The installation process is done through the joining of segments throughout the launching construction phase. The cross section of the bridge is presented in Figure 2.

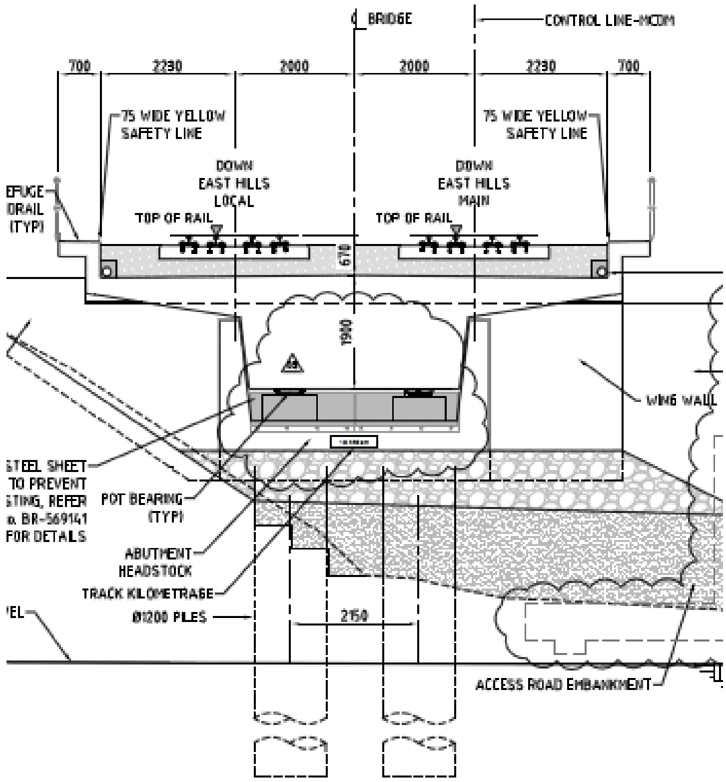


Figure 2. Cross-section 2 of the Salt Pan Bridge.

3. Modelling

The Discrete Element Method (DEM) is a computer modelling simulator which models the behaviour of geotextile soil systems through accurate modelling and large displacements. The DEM is capable of dealing with the insertion and removal of particles in both two dimensional and three dimensional cases, which is vital in the practical use of the computer program in modelling structures. The use of the DEM is used to model the behaviour of a railway ballast structure under different pressures and types of loading applied to the rail super and substructure. Furthermore, the traditional size of ballast averages around 40mm and common errors in analysis and diagnosis of the substructure is the assumption that the ballast moves in one piece. Moreover, due to the various particle sizes, this suggests that an analysis should be undertaken through simulation and modelling of sections of the ballast. This is carried out to identify and investigate the movement of these individual ballast particle grains within the substructure. The DEM model allows this analysis to be carried out by modelling and tracking the movement of the individual particles under forces and consequently the impacts that these movements have on the overall structure. Crushable and ballast particles are used to represent the ballast grains in the DEM which are usually in the form of agglomerates of ballast bonded together. Through the analysis carried out on the ballast structure, failure in areas of the ballast can be explained and therefore analysed to provide efficient and correct diagnosis [7-9].

Through the use of ABAQUS, the ballast can be modelled with precision in accordance to the Salt Pan Bridge specifications. The platform allows construction of each material and section required to correctly analyse the component under cyclic loading. Each particular element of the model is created in a 3D workspace where the subject can be detailed to its exact properties and capacities. More complexly, the damage implicated upon the ballast structure and its deflection can be analysed. The advanced applications of the program give viable reasoning for its common use in the engineering community. The Slat Pan Bridge ballast component is the focus using DEM to provide results on the stress and strains from cyclic loading. This element is the most critical of the railway infrastructure as it's the supporting foundation for the sleepers and other components [10-12]. Through creation of a ballast structure and applying realistic loadings, purposeful results can be obtained to aid in the maintenance and repair of the Salt Pan Bridge. Visual and statistical data of the railway bridge's critical element are both provided and the information can be easily employed. The model of bridge-track interaction is shown in Figure 3.

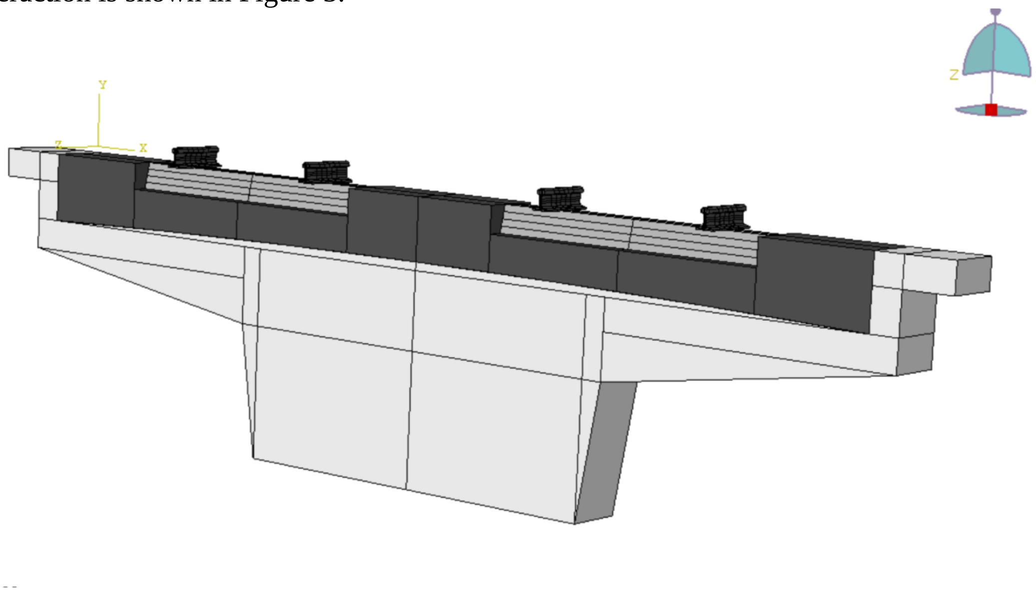


Figure 3. Total bridge-track model (ballast is modelled using internal discrete elements).

4. Materials

4.1. Ballast

The ballast specifications according to AS 2758.7 encompassing rock aggregates for railway ballasts sets minimum standards for Australian rails [13]. This study has adopted the specification and modelled their constitutive behaviours as in Figure 4.

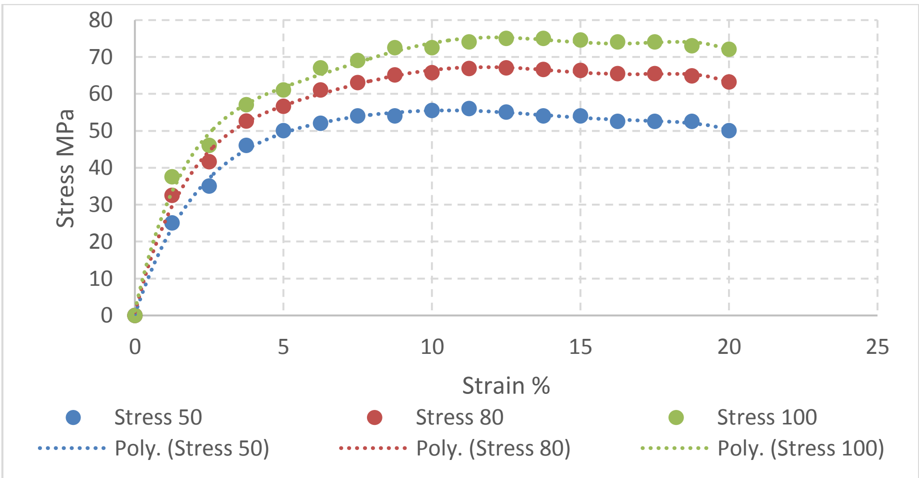


Figure 4. Ballast stress-strain relationships.

4.2. Concrete

Figure 5 represent nonlinear behaviour of concrete used in this model.

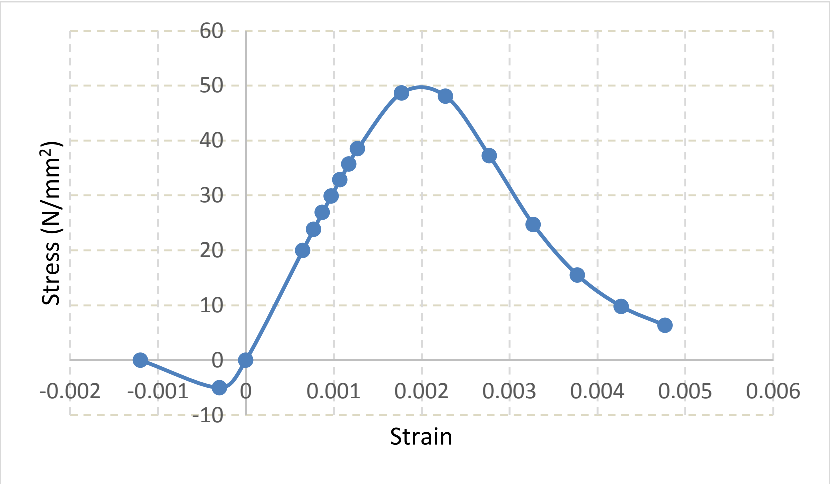


Figure 5. Concrete stress-strain relationship (50MPa).

4.3. Steel

Bi-linear behaviour of steels has been adopted for this study, which can be tabulated in Table 1 [14-18].

Table 1. Stress-strain relationships of various steel elements.

Element	Ultimate Stress	Plastic Strain	Ultimate Strain
Steel Beam	1.28 x Yield Stress	10 x Yield Strain	30 x Yield Strain
Steel Reinforcing	1.28 x Yield Stress	9 x Yield Strain	40 x Yield Strain
Profiled Sheeting	-	20 x Yield Strain	-
Shear Connectors	-	25 x Yield Strain	-

5. Dynamic moving load

For design purpose, the loadings onto the steel rails in accordance with the Australian Standards AS5100.2 will be used to calculate the most critical force, which will act on the rail. Figure 6 below is an illustration, which was used in order to extract the most critical force. For the purpose of this 3D analysis, it is paramount that the ENCASTRE setting was selected as the boundary conditions in order to fix the bottom of the concrete section in all directions (x, y, z).

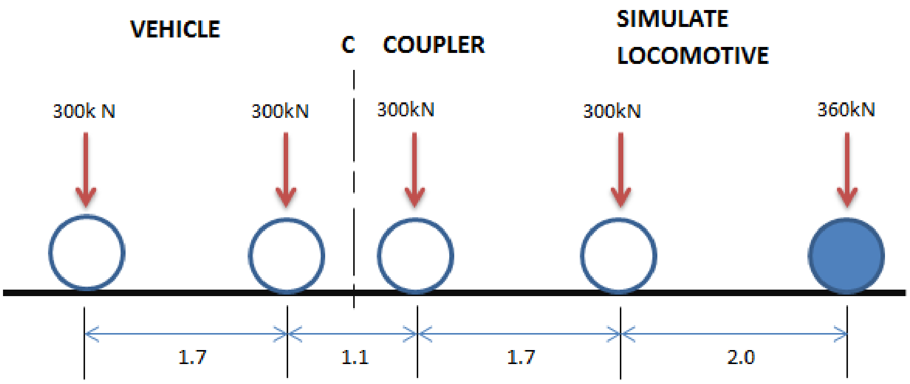


Figure 6. AS5100.2 Steel rail loading.

6. Results

The results for the steel rail were obtained from FE modelling. The steel rails yield stress value is 780MPa. Figure 7 displays stress distribution throughout the steel rail when dynamic loadings are applied. The stress concentration is accumulated in the region where the distributed loads are applied. The stress distributed evenly through the steel rail and transfers to sleepers.

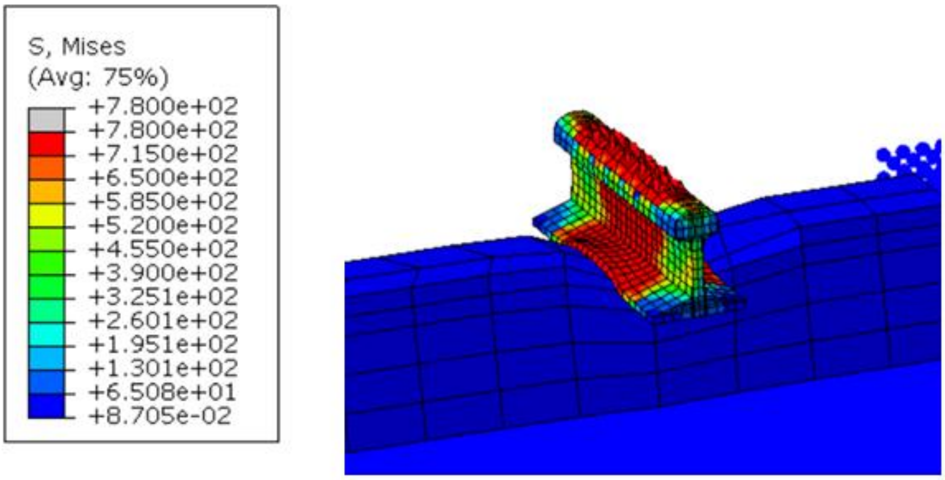
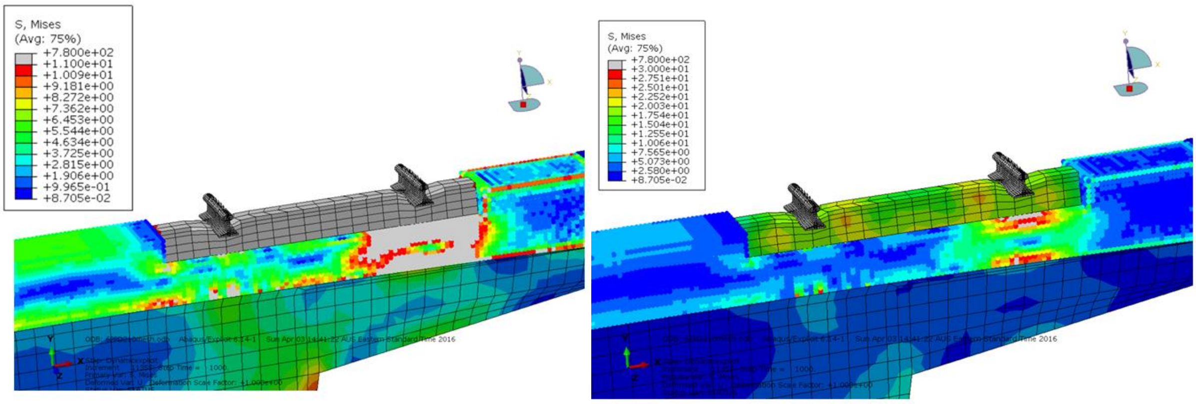


Figure 7. Results within the steel rail.

Figure 8 also, displays stress distribution throughout the concrete sleeper when dynamic loadings are applied. The stresses are distributed evenly throughout the concrete sleeper with some concentrated stress located between the steel rails. Illustrated in Figure 8, the stresses within the concrete sleepers are greater than the yield stress value however lower than its ultimate stress value. The stresses are distributed evenly through the concrete sleeper and transfer to the ballast.



a.) 11MPa stress limit b.) 30MPa Ultimate stress limit

Figure 8. Results within the concrete sleeper.

The ballast has an ultimate stress of 66.8MPa and yield stress of 32.5MPa. Analysis of the ballast component in Figure 9 illustrates ballast failure as the yield stress is exceeded. Due to the stress being greater than yield, permanent deformation occurs. Point A directly below the outer steel rails shows the region where yield occurs within the ballast when the yield limit is set as 32.5MPa.

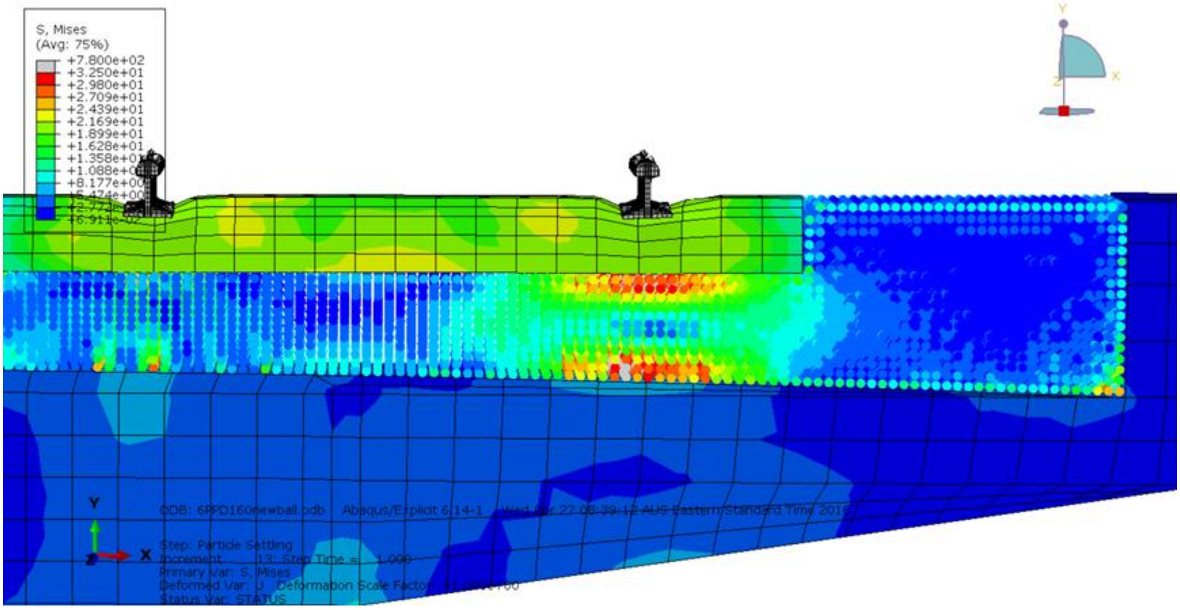


Figure 9. Ballast results showing yield at bottom section below rail.

7. Conclusion

Overall, a hybrid DE/FE model has been achieved in order to analyse the ballast behaviour under dynamic loading. In addition, dynamic stresses and strains have been obtained for all track components to provide visualised results at the contacts between the steel rail and sleeper, as well as the sleeper-ballast interaction. The DE/FE models showed that the ballast granular media on the Salt Pan Bridge Railway dilate after their stress exceeds the yield limit of 32.5MPa. These results support the current problems of ballast found in the field. The hybrid DE/FE stimulation also illustrates that high ballast stresses occurred directly below the outer rail where the yielding takes place. The DE/FE analyses conclude that the 50MPa concrete bridge deck is insignificantly affected by the dynamic loading. The highest stress patterns noticeable in the section are where the web meets the flange. However, there were micro-cracks present in the section mentioned above. The DE/FE model shows that there are high concentrations of stress in the corners of the ballast bed, due to the bow section. Forces acting on the rails are likely to increase this bow effect causing stress at these focal points. The DE/FE analyses undertaken found that the steel rail does not yield when experiences dynamic loadings.

Acknowledgments

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